Booster 15Hz Operation

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March 4, 2014

Scope

- **Brief History of Booster RF systems**
- **RF system description**
- **Modifications over the years**
- **Booster Solid State RF upgrade project.**
- **Upgrades required to achieve 15 Hz beam operation.**
- **Booster RF cavity**
- **Other RF issues.**
- **Summary**

Brief History

- **Booster cavity design started at Lawrence Radiation Laboratory in the 1960's.**
- **Comprehensive study to evaluate ferrite toroid manufactures with specific properties suitable for electronic tuning a coaxial accelerating cavity over a frequency range of 30Mhz to 52.8MHz. Toroid size: 8" OD x 5" ID x 1" thick.**
- ***Settled on NiZn toroids manufactured by Stackpole (mu=12) & & Toshiba (mu=40).***
- **Producton cavites & tuners built by GE in Schenectady, NY**

Booster RF Cavity Pair Delivery X-Gallery

July 1970
Flatbed semi delivering Booster RF cavity pair with original one piece girder to X-Gallery.

Booster RF Cavity Pair Delivery X-Gallery

July 1970 – Single one piece girder with two RF cavities at x-gallery high-bay – ready to be lowered into Booster staging area.

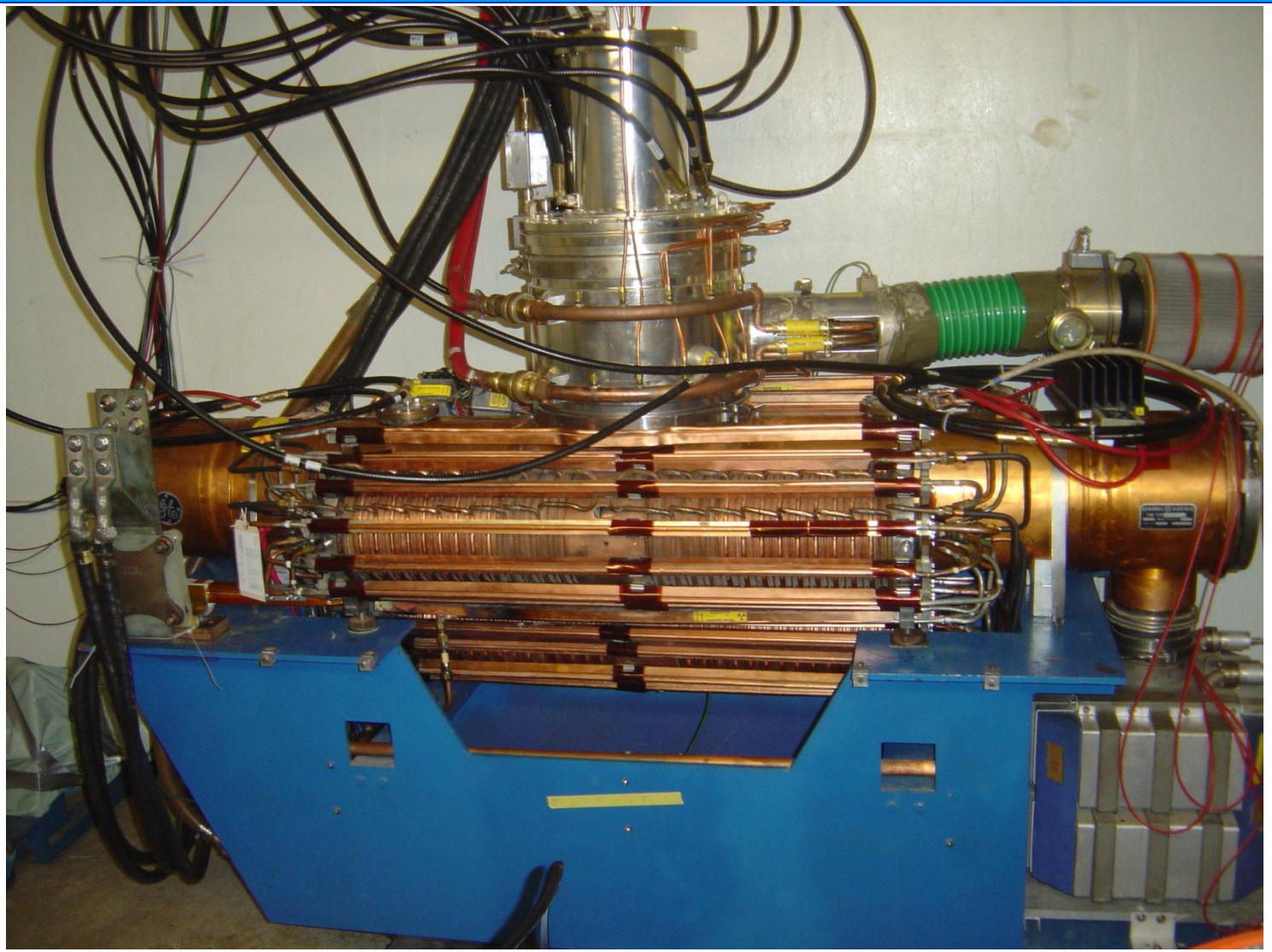
RF System Description

- **Normally 19 High level RF stations installed and operational but with current cavity refurbishment only have 17 stations active.**
- **Typical RF station consists of a fast slewing 0 to 2500 Amp Ferrite Bias Supply, 30 kV Series tube modulator, 150 kW power amplifier, RF cavity with 3 tuners + HOM dampers, & local station controls.**
  - 10 stations in the West Gallery run off one outdoor anode supply.
  - 9 stations in the East Gallery run off another outdoor anode supply.
- **All 19 stations are upgraded with 4kW Solid state driver assembly, new 30kV Series Tube Modulators, new 150 kW Power Amplifiers (St 12 upgraded in 2001 (prototype) and St 19 in 2005).**
- **Booster cavity parameters**
  - Frequency sweep – 30 to 52.813 MHz, present sweep 37 to 52.8 MHz due to 400MeV Linac upgrade.
  - Q at injection (37MHz) ~ 325, Q at extraction (52.8MHz) ~ 1250
  - Peak accelerating voltage per cavity ~ 50 kv

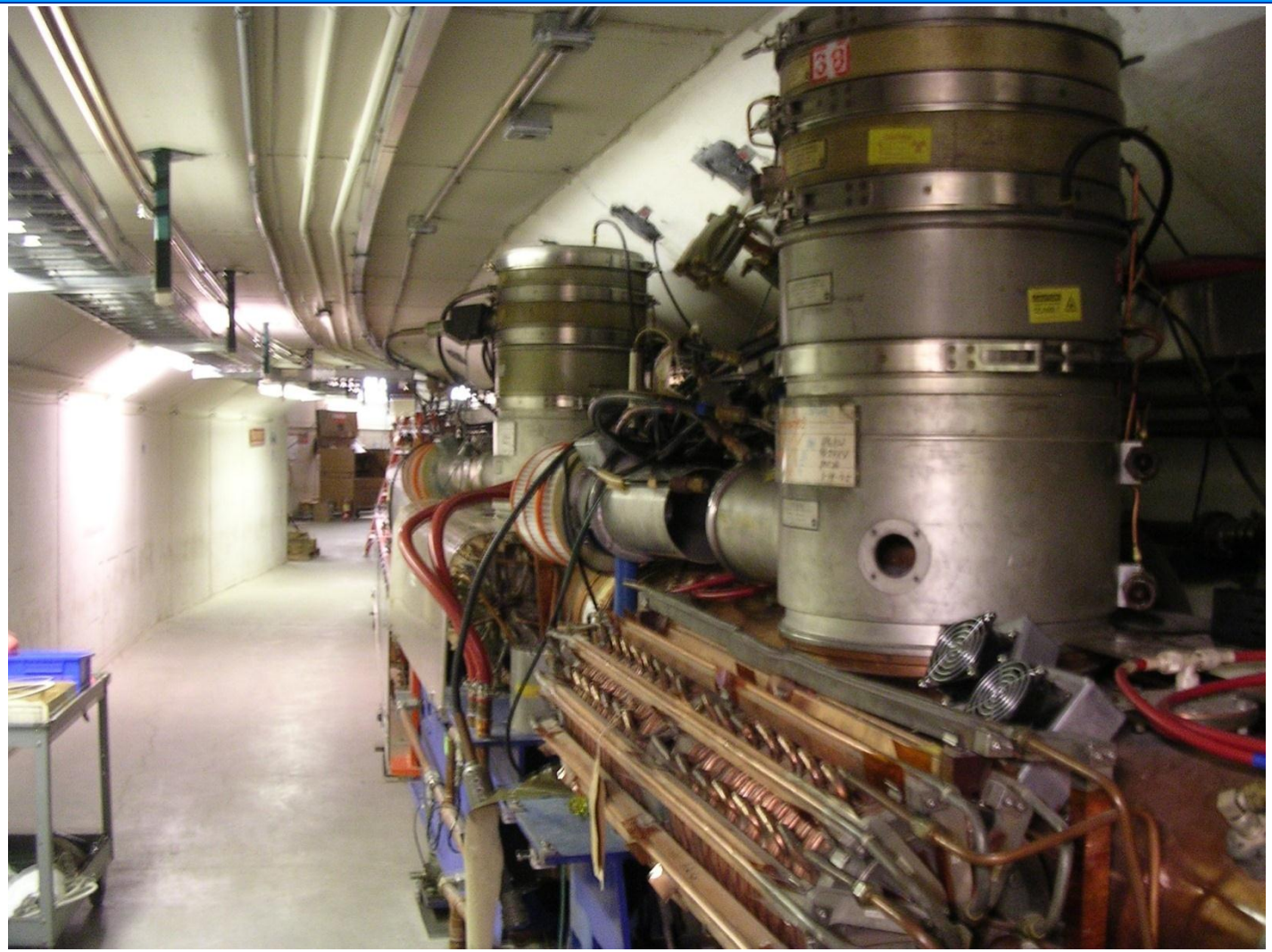
Modifications / Upgrades – Early Years

- **Booster RF cavities were modified in the mid to late 70's with the following upgrades:**
  - Upgraded spark detection system.
  - Monolithic RF coupling capacitor with metalized interface to copper spinning's for coupling PA output to RF cavity.
  - Girders split into two separate structures to facilitate change-out
  - Tuners rebuilt using new lower loss ferrite to replace M4C21A
    - Replaced 10 Toshiba M4c21 cores (mu=40) with 10 Toshiba M4D21a cores (mu=20) in each tuner.
    - 18 Stackpole CeraMag 14 material toroids (mu=12) remain unchanged.
  - Cavities
    - Tuners removed for rebuilding
    - All components thoroughly cleaned
    - Electrical joints tin plated
    - Mode damper mounts add

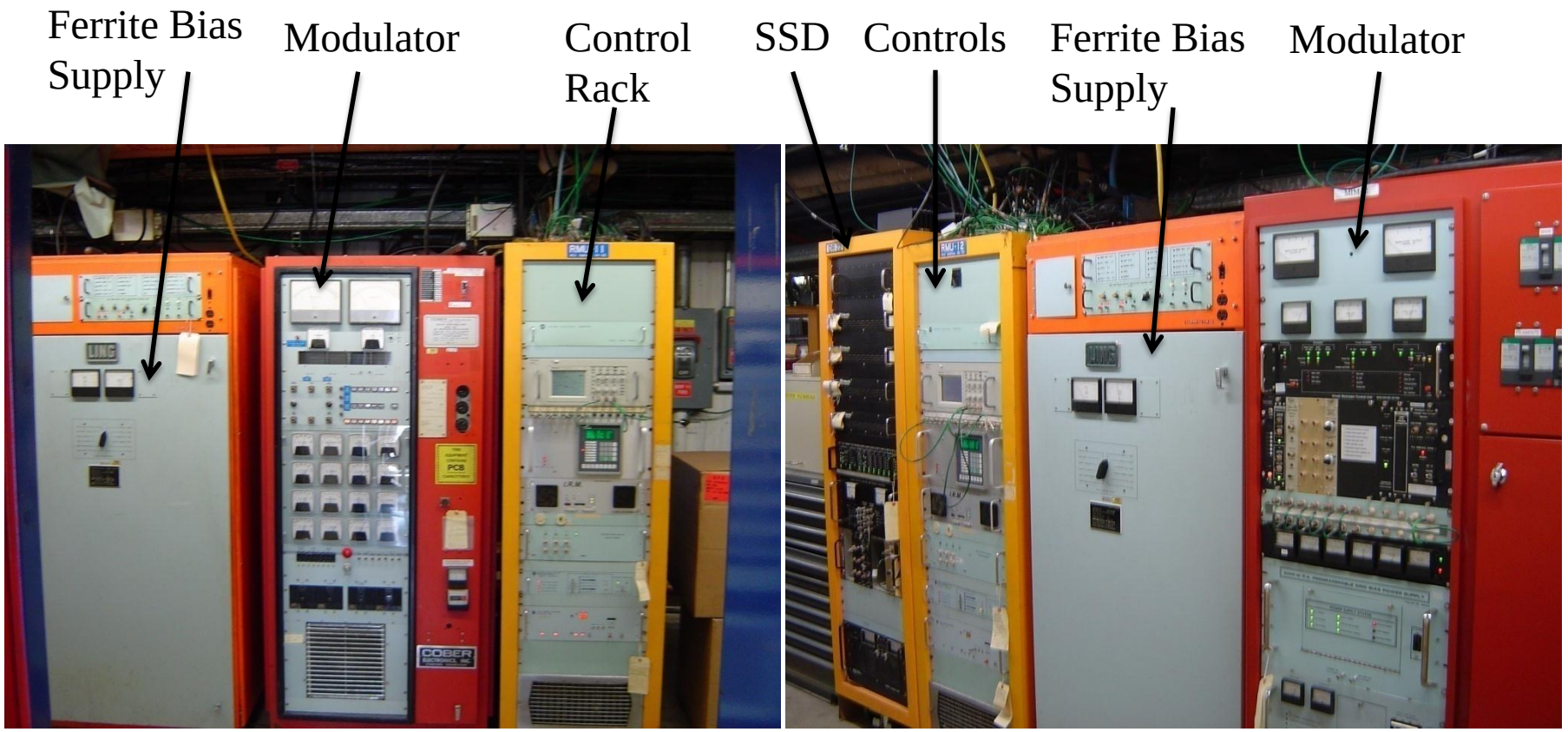
Booster RF Cavity



Installed Pair of Booster RF Cavities



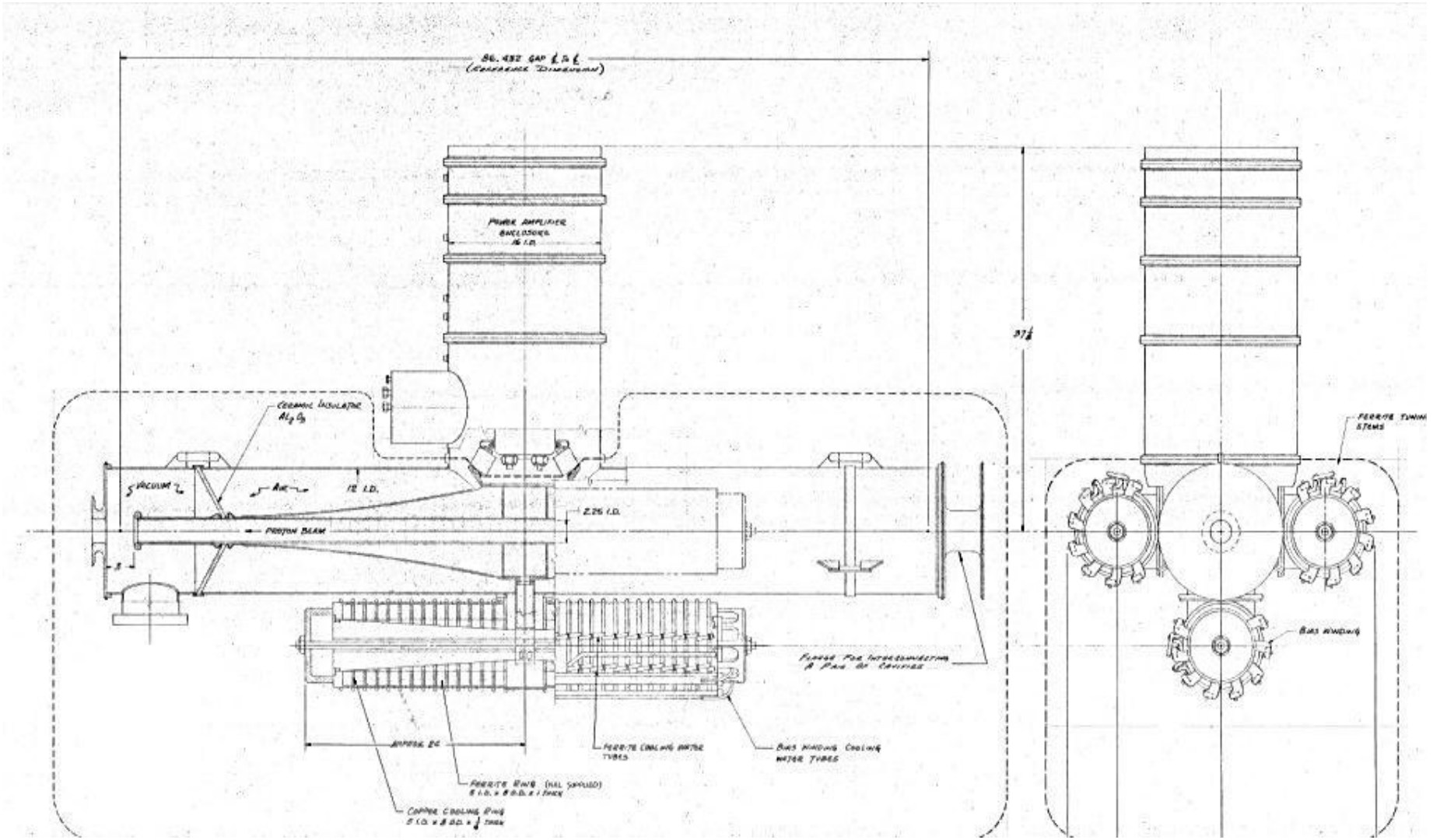
Typical Booster RF Station



Original Booster RF Station

Upgraded RF Station with SSD + New Modulator

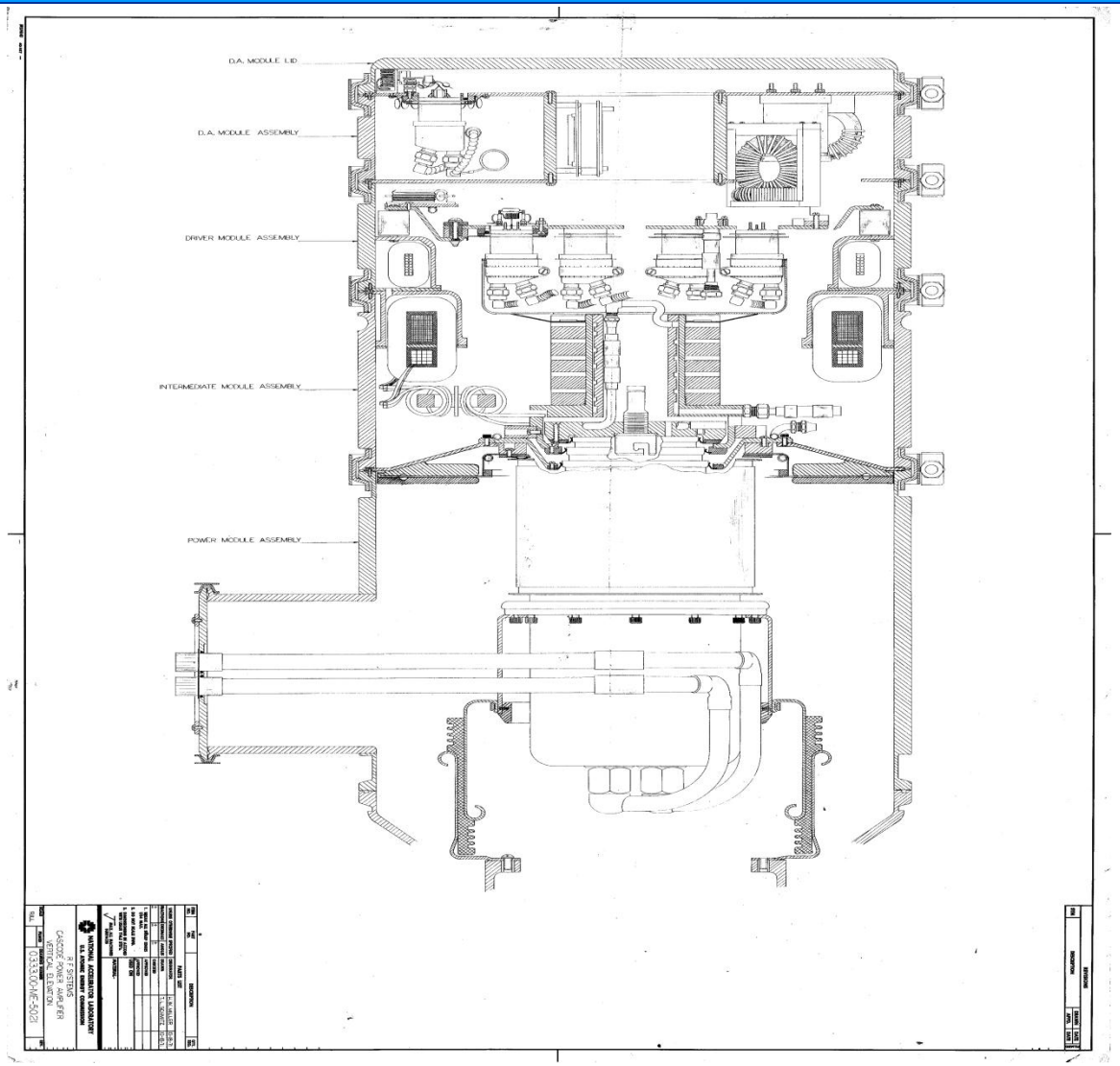
Booster RF Cavity



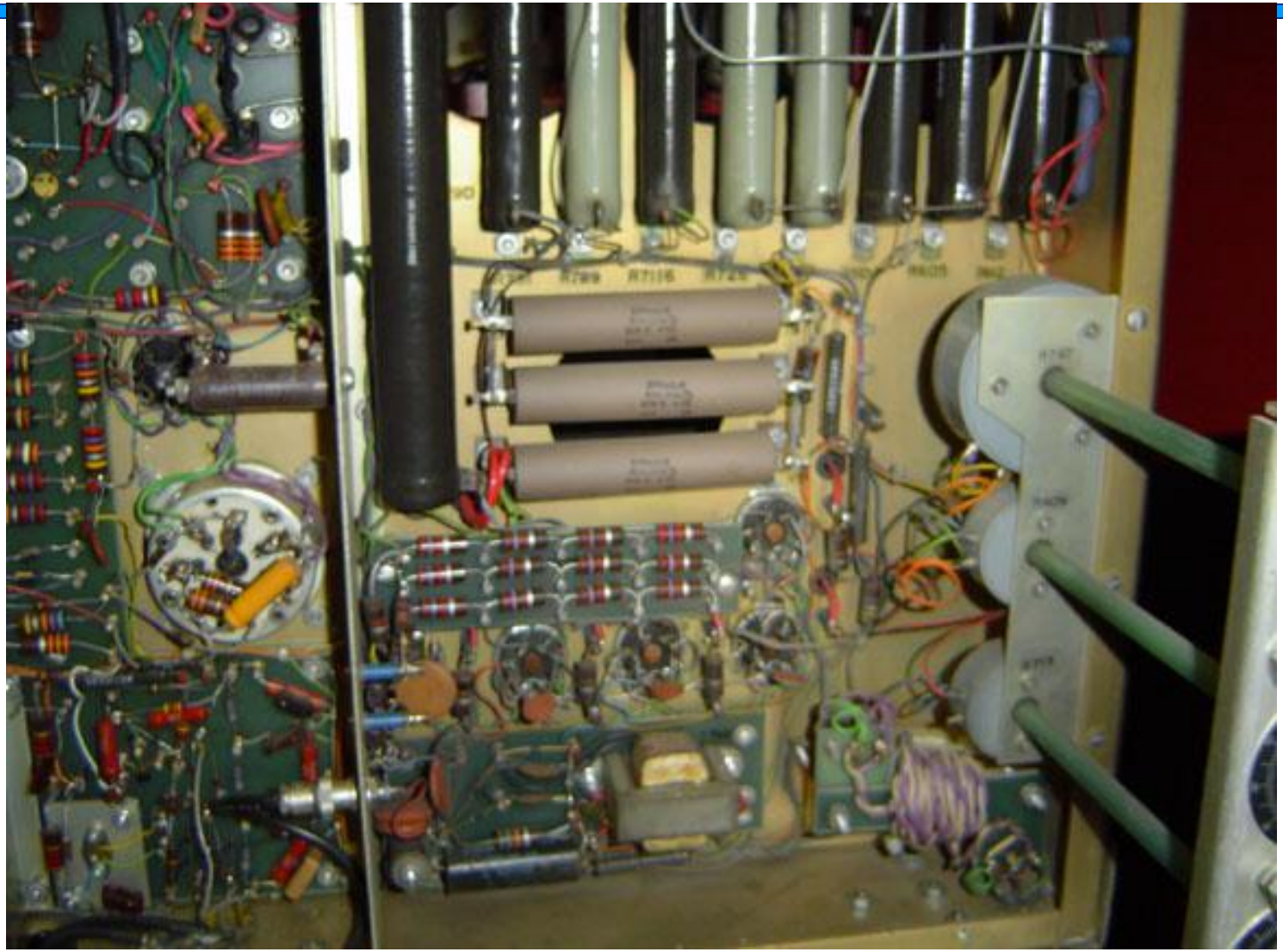
Original Equipment until 2012

- **Modulators**
  - Relics of the past, outdated from day one. Use technology from the 50's.
  - Very few PC boards, mostly point to point wiring.
  - Use a number of glass vacuum tubes, some getting harder to find.
- **Ferrite Bias Supplies**
  - Replaced original Ling power supplies with FNAL design units in the early to mid 70's due to original Ling power supply poor pulsing performance, both electrically & mechanically.
- **Power Amplifiers**
  - Consist of three sections
    - 6 water cooled 4CW800F tubes - distributed amplifier – life ~9-12 months
    - 14 water cooled 4CW800F tubes - Cascode amplifier –life ~9-12 months
    - 1 water cooled Y-567B tube – Power module – life ~ 36 months
  - Typical repair time for original Booster Power amplifier was ~ 60 man hours and cost of 4CW800F's getting extremely high.

Old Style PA's

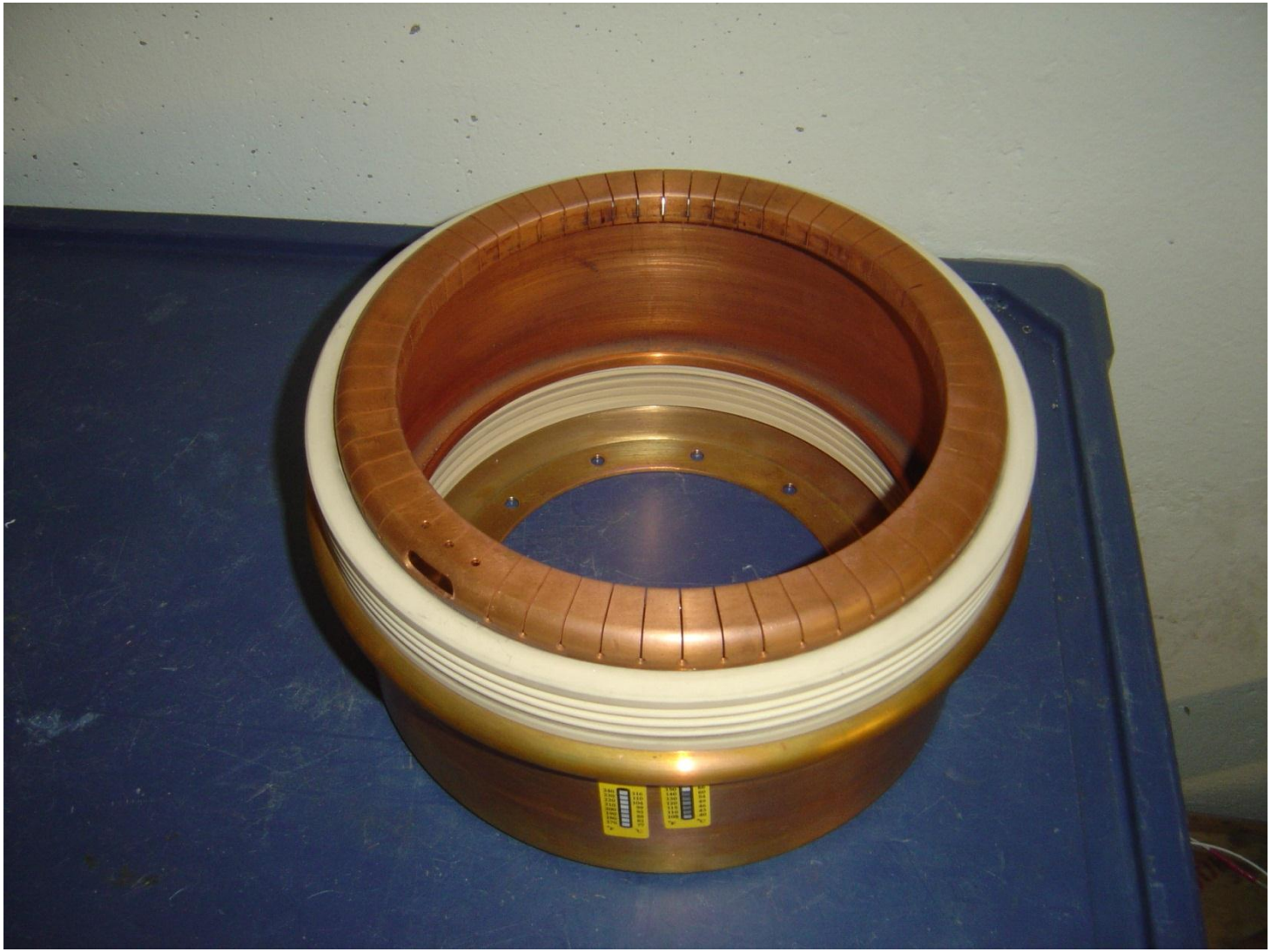


Original Modulators



Original Modulators

Monolithic PA Anode Coupling Capacitor



Preparing for 15 Hz RF System Operation

- **Booster RF presently running at ~ 7.5 Hz.**
- **To satisfy program demands, need to run 15 Hz continuous.**
- **Booster RF reliability has been a significant matter for discussion over the last 12 + years.**
  - RF system never capable of operating at a continuous 15 Hz, only ran in burst mode at moderate duty factor.
  - Increased demands on the duty factor started with the beginning of MiniBooNE operations in 2002
  - NuMI/MINOS demands have greatly increased the demands on Booster.
  - Original equipment > 40 years old.
  - Need to maintain a minimum of 900Kvolts / turn ~ 50kV/ station
  - Spare Station 19 acts as hot spare to compensate for a down station.

Modifications to Achieve 15 Hz

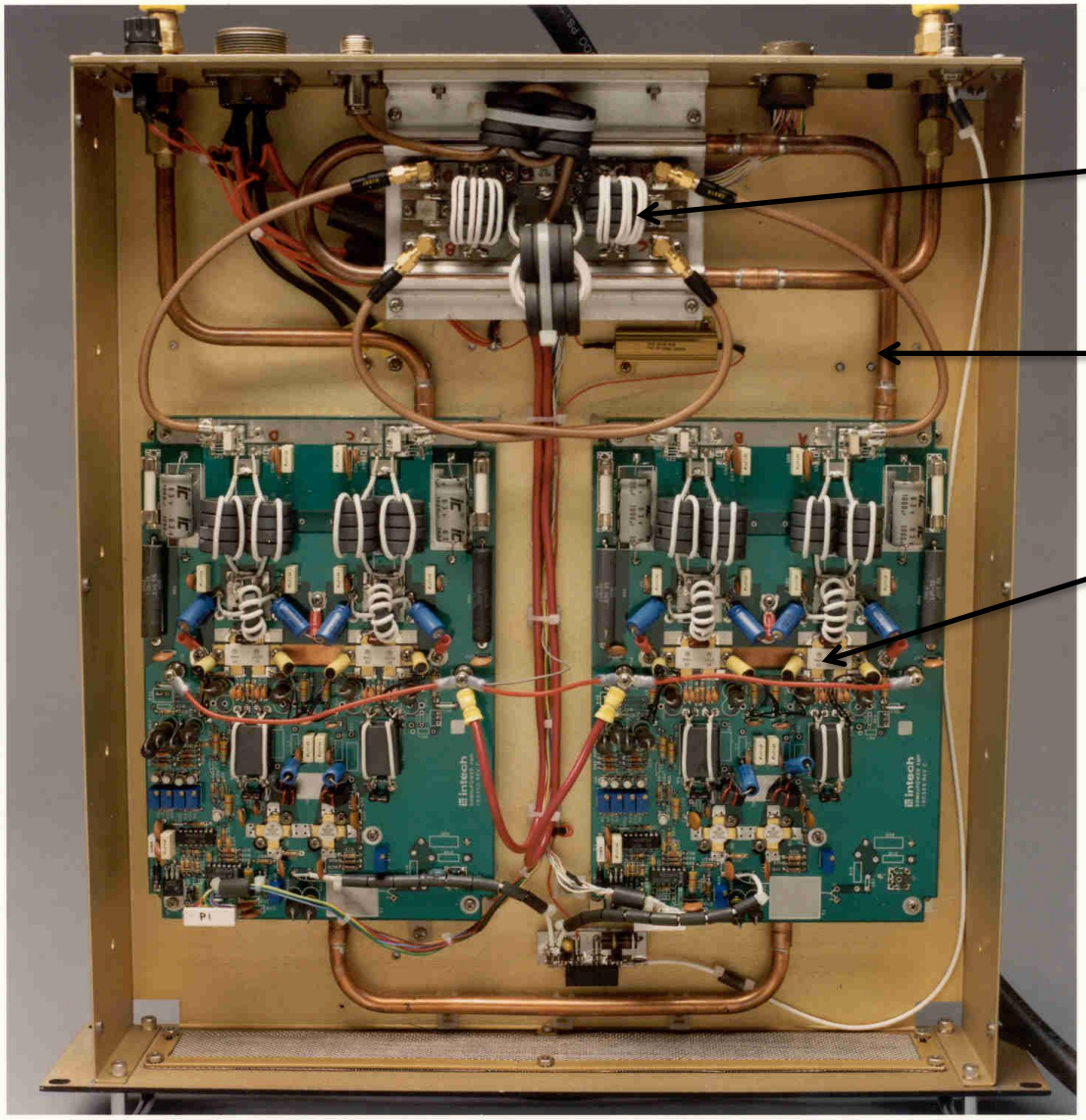
- **Required Modifications for 15Hz operation,**
  - Completed the Solid State Driver Upgrade project, March 2013.
  - Reconnect the ferrite cone cooling lines which were disconnected many years ago due to low duty factor operation.
  - Install new copper clad skins on tuner cone castings
  - Machine cavity tuner interface surfaces flat and parallel for good high power RF connections.
    - This requires removing cavities from tunnel and cycling tuners & cavities through a rebuilding process.
    - All cavities are run through the MI-60 test station and tested at a 15 Hz rate for a minimum of 168 hours of which 120 hours at full gradient before reinstallation in Booster tunnel.
- **Would like to have a second high power test stand at F0 to do long term testing of a refurbished cavity**

Solid State Driver Upgrade Program

- **Upgrade Program**
  - Build 22 new FNAL designed modulators (identical to MIRF).
  - Build 22 new FNAL designed 150kW power amplifiers
  - Build 22 new FNAL designed 4kW solid state driver amplifier assemblies.
  - Replace all RF station cabling to the tunnel (HV, ½" Heliax,
  - & all control cables.
- **Present Status**
  - Completed solid state driver upgrade project in March 2013.
  - Final project cost was under original cost estimate.

1 kWatt Solid State RF Module

1 kW SS RF Amplifier Module

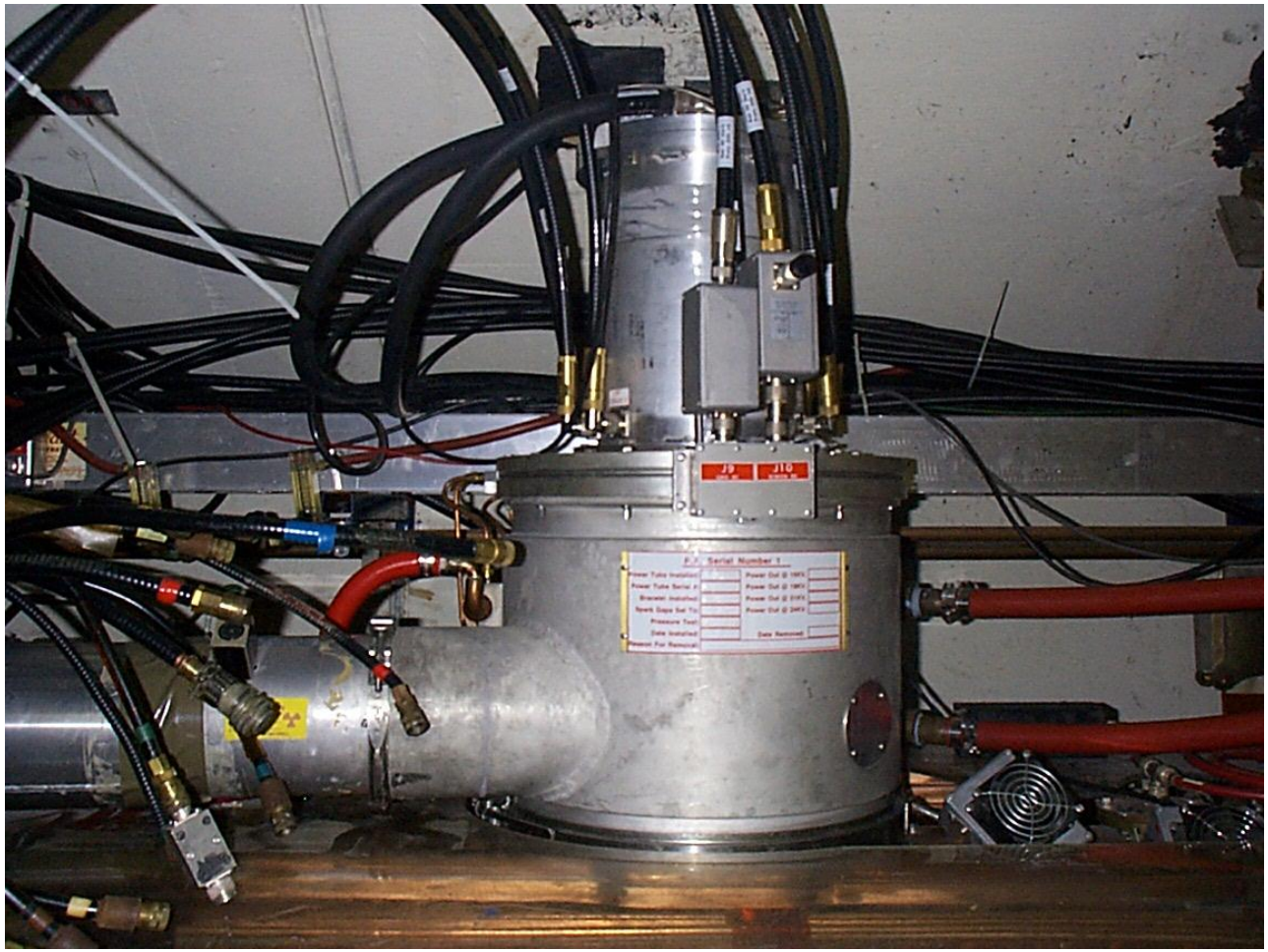


4-way combiner

Water cooling

Each ckt board contains two MRF-151G MOSFETs producing ~250 watts per channel

Booster St 12 Amplifier



New 150 kW power amplifier on station 12's cavity

Solid State Driver Amplifier Racks

New Modulators

Additional Scheduled Booster RF Upgrades - PIP

- **Anode Power Supplies**
  - Two new power supplies to replace original 1970 power supplies
    - Includes new 13.8kV Step Start VCB contactors
    - New 2MVA transformers
    - New outdoor DC Cabinets with HV components
    - New controls
    - Completion in FY15-FY16
- **Ferrite Bias Supplies**
  - Replace marginal Main Rectifier Transformer & SCR packages in 10 West Gallery Supplies.
  - Project started in FY14 and scheduled to be complete in FY15.
  - Completion does not limit prior 15 Hz operation.
- **Build 3 new Booster Cavities with slightly larger aperture 3.25”**
  - Would install cavities for NEW Booster Stations 21 and 22.
  - Preliminary design considerations based on modeling (Simulation from M. Hassan in TD) is underway.

Cavity Refurbishment

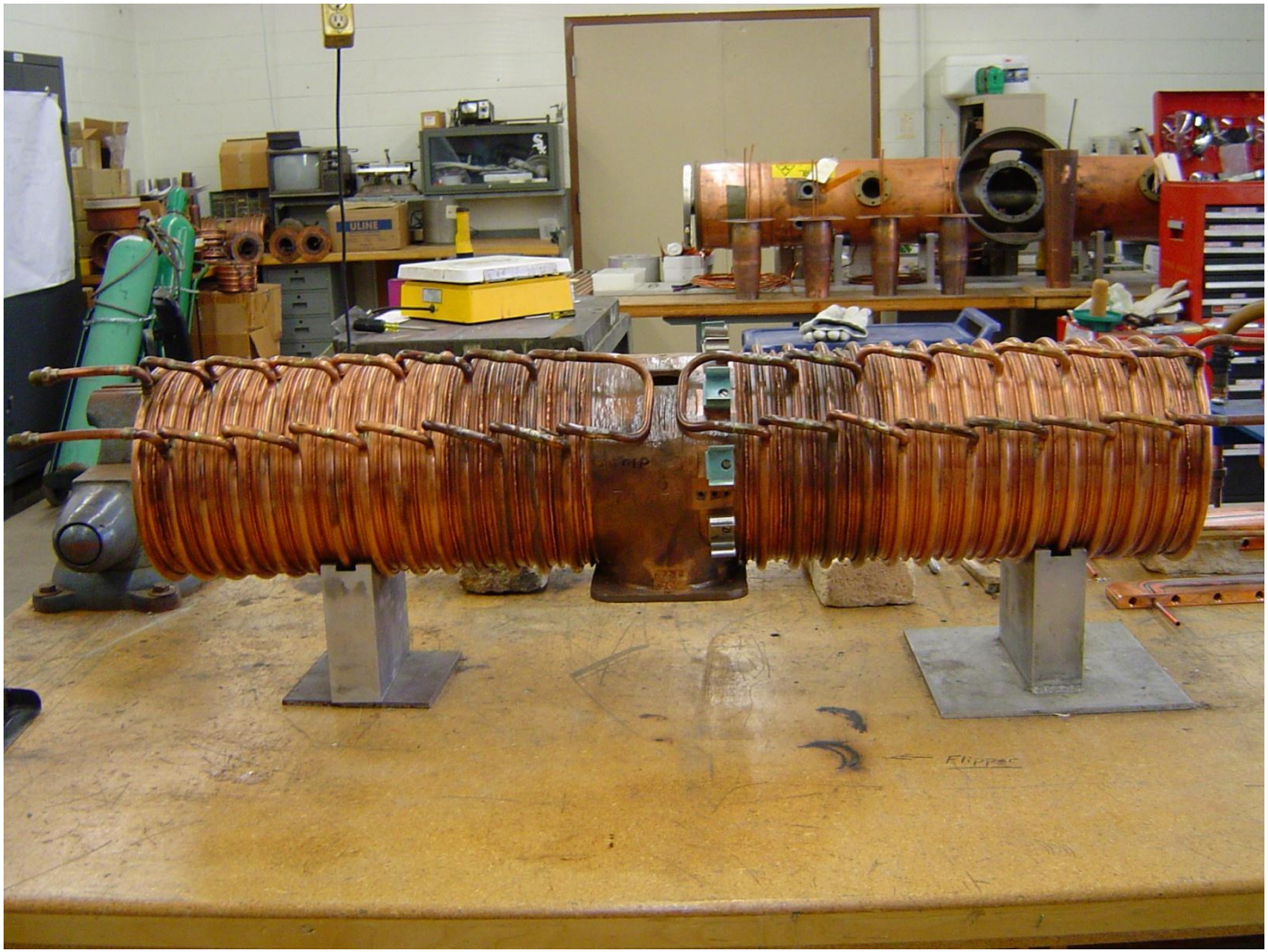
- **Completed 9 of 19 cavities with the 10 th cavity currently running in the MI-60 testing .**
  - The first two cavities that were refurbished had to be redone after a number of months of operating time in the machine due to tuner stem arcing.
  - All other refurbished cavities have run to date without problems.
  - On going learning process as additional rebuild issues arise.
    - Cavity end flange (pie tin) vacuum leaks.
    - Water cooling tube leaks on center casting.
    - Concentricity of center casting in outer shell.
- **Takes about 8-12 weeks per cavity for refurbishment.**
- **Some cavities are more radioactive than others (upstream cavities are the most radioactive) with a few of them Class 3.**
- **Rebuilding tuners takes the most time.**
- **Have procured & tested additional 200 low mu ferrites and waiting on the vendor to finalize high mu (mu=20) toroids.**
  - With the procurement of low and high mu toroids + cone castings, an additional 10 tuners can be built which would accelerate our turnaround time and supplement our tuner spares.

Cavity Installation Schedule

BRF	15 Hz Status	Cavity S/N	Date Installed
1	Refurbishment Complete	1009	4/22/2013
2	NR	1006	
3	No cavity	1011	
4	NR	1002	
5	Refurbishment Complete	1008	9/24/2012
6	Refurbishment Complete	1017	11/14/2012
7	Refurbishment Complete	1018	10/23/2013
8	Refurbishment Complete	2002	12/4/2013
9	NR	1	
10	NR	3	
11	Refurbishment Complete	1007	6/26/2013
12	NR	1019	
13	No cavity		
14	NR	1010	
15	Refurbishment Complete	4	6/26/2013
16	NR		
17	Refurbishment Complete	1005	
18	NR	1016	
19	Refurbishment Complete	1012	2/18/2014

Standard Booster Cavity Bore - 2.25”

Booster Cavity Ferrite Tuner housing with Ferrites only



Tuner Cones

Bare copper castings with single turn cooling loop

5 mil Cu clad stainless skins

Cavity Traveler

		Tuner cone leak check	Tuner cone fingers	Stem Condition	Replace Cone	Tuner Refurbishment notes
Cavity S/N	1005					
Removed from Station #	17					
Date Removed						
Date Shipped to MI-60	7/1/2013					
Front Tuner S/N	47					
Bottom Tuner S/N	29					
Back Tuner S/N	22					
Ion Pump Tag #						
Refurbishment start date @MI60	7/1/2013					
Check Stem connection to center casting	7/3/2013					All three flanges need copper fill weld.
Weld copper material to center casting if necessary	July 9 and July 11					
Flatten all three tuner flanges on cavity	19-Jul					
Clean cavity	23-Jul					
Electrical test of Bottom tuner	Tuner 11/July 1st					
Electrical test of Back tuner	Tuner 29/July 26					
Electrical test of Front tuner	Tuner 10/July 26					
Installed refurbished tuner Back	Tuner 29/ July 31	Has a .030 copper shim with no lip.				Both cones have new brazed cooling cones
Installed refurbished tuner Bottm	Tuner 11/ July 24	Has a .062 with .030 lip				Both cones have new brazed cooling cones.
Installed refurbished tuner Front	Tuner 10/Aug. 2nd	Has a .015 shim with no lip.				
Install plumbing	5-Aug					
Leak check cavity - LCW						
Leak check cavity-helium	5-Aug					
Notes	All electrical bus bar are connected. The block connection (front tuner) had 10/32 threads missing. It had ¼ clearance hole, so a bolt with brass nut was used for connecting.					
Vacuum Leak check cavity						
Final assembly of cavity with Blocker + PA						
Date moved into test cave						
Date start of electrical testing						
Date Finished of electrical testing						
Date shipped to Booster						
Date installed in tunnel						
Installed into St Number						

Cavity traveler + detailed logbook entries keeps good documentation for refurbishment process.

Other RF Issues

- **Increase mode damper power dissipation (load).**
- **Replace old rf sum balancing circuit with new global amplitude & phase regulator circuits so amplitude and phase of "A" stations and "B" stations track the request.**
- **Rebuild prototype Booster rf cavity using spare production center castings (inner & outer) to achieve a good operational spare. Start Jan 1, 2011.**
- **Need to get acceptable mu=20 toroids from vendor before starting assembly of 10 spare tuners.**
- **Add direct RF feedback to each station to reduce beam loading effects for added stability under possible higher beam currents.**

Summary

- **Continue to refurbish Booster RF cavities & tuners shooting for an 8 week turnaround.**
- **Implement Global Amplitude & Phase control .**
- **Finish assembly of one additional girder assembly with cavity assembled (referred to as cavity 20) from out of tolerance center casting and select components from the original welded prototype cavity. Bare cavity is complete but waiting on new tuners for assembly.**
- **Procure spare tuner cones.**
- **Build 10 additional spare tuners (TD) to supplement our current 4 spares.**
- **Install diagnostic measuring devices on a couple of the existing RF cavities in the tunnel to track thermal heating.**
- **Replace old rf sum balancing circuit with new global amplitude & phase regulator circuits so amplitude and phase of "A" stations and "B" stations track the request.**
- **Increase mode damper power dissipation (external loads).**